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学 位 論 文 題 目	Application of principal component analysis in investigating time series of remotely sensed data（主成分分析による衛星データの時系列解析）
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学 位 論 文 の 内 容 の 要 旨

The issue of analyzing time-varying phenomena of various kinds occurs in a wide variety of fields such as daily stock price fluctuations in stock markets, weather forecast based on past data, design flood computation based on historical flood data, and so on. Phenomena of this kind have a common characteristic that they constitute a series of past data, which form a basis to analyze their trend and, if necessary, predict the future state of the phenomenon in question. The set of historical data that represents the progress of a phenomenon over time is known as time series and the scientific analysis of such data sets is known as time series analysis (TSA).

In the field of remote sensing, evaluation of changes in natural processes is a major area of interest for researchers. TSA is often discussed in conjunction with the change analysis as a way of understanding how the process changes over time. Because of the growing availability of synoptic digital data, in the form of satellite imagery, covering large swaths of earth surface, the general direction of research in change analysis has been in finding ways to automate the process with the help of computer-assisted analysis. Satellite imagery of earth's surface constitute the most commonly available form of time series data in remote sensing.

In this research, the broad objective is to assess the potential of PCA as a time series analysis tool in remote sensing. This has been accomplished by using PCA for analyzing Landsat/TM data, and evaluating the results. The state-of-the-art of the TSA is first reviewed. The review of available literature indicates there is a general lack of sophisticated methods for time series analysis of satellite image data. Contemporary literature suggests that one line of research attempted in feature extraction from time series data involves applying various kinds of mathematical transformations to multi-spectral bands. Some of the transformations commonly employed

include band ratioing, Fourier transforms, wavelet transforms etc. In this study, a transformation method called principal components analysis (PCA) is applied to the time series data consisting of Landsat/TM images covering a time span of 18 years from 1984 to 2002. The target study area is Tottori city and its surroundings. Because of the statistical steps involved in PCA, this method transforms the input data into a set of mutually uncorrelated components. The reason for using PCA for analyzing the time series is the expectation that some of the relevant characteristic features, which in this study are changes in landuse and thermal environment, would be reflected in one or more of the component images.

Here, two types of time series data are collected and analyzed. One set consists of a total of ten same-season TM images from 1984 to 2002. The second set consists of four seasonal TM images for the year 2002. Geometric correction is applied to all image data before processing. This correction involved georeferencing the images with respect to ground control points obtained from existing topographical maps. First-order polynomial with the cubic convolution resampling is used in georeferencing. Due to geometric correction, all data are reduced to the same projection and the same pixel size. Spatial error of less than 18m is achieved in resampling.

The seasonal and non-seasonal image data are grouped into bandwise time series data sets for the purpose of feeding into the PCA algorithm. For example, a PCA analysis on the band6 series (thermal band) is used to investigate the thermal environment in the study area. Similarly, separate PCA analyses are conducted on some of the visible and near-infrared bands, and also on NDVI time series. In addition, PCA analysis on a large time series consisting of all the seventy bands of the ten non-seasonal data sets is also conducted. Changes in thermal environment and landuse, and seasonal changes are evaluated and such changes are interpreted in terms of PC components. Effort is made to explain the trends in changes in terms of uncorrelated components derived from PCA. A gradual upward trend in the thermal environment is observed in the urban areas. This trend closely correlates with the urban expansion as determined by landcover change analysis. Another significant trend in landuse change is the increase in forest and urban classes, which has occurred primarily at the expense of agricultural class.

The distribution of variance among PC components shows that the TM data are highly correlated. This is seen by the fact that a very large percentage of the variance is accounted for by the first few components, while the majority of later components do not exhibit any readable information. In the case of PCA on all seventy images, for example, the first ten components explained more than 96% of the variance while the remaining sixty components totaled less than 4%. Most components later than about 20^{th} component seem to contain no useful information. Thus, it is seen that PCA is quite useful in greatly reducing the effective dimensionality of the input data sets, and thereby facilitating feature extraction from a large time series.

It is found that the changes in the thermal environment and other landuse changes are reflected in some of the earlier PC components. The first component is found to be better for visual feature extraction than any of the input data sets individually. Specifically, the false color composite constructed from the first three components proved to be visually most appealing than any of the false color composites achievable from the original bands. The first few components after the first one usually proved to be useful in discerning the subtle changes in the underlying phenomena. In the case of thermal-band time series, the second component closely reflected the thermal changes. In other time series data, the second component usually highlighted the urban sprawl as well as rivers and streams, whereas the changes in major landuse class reflected in the second and third components. Thus it is obvious that, despite the low amount of overall variability, two or three components starting from the second are most important in reflecting thematic information from the time series.

The results of the study show that PCA techniques can be a promising method to analyze long time series data composed of satellite images. From this study, it can be expected that, with sufficient further research, it should be possible to develop algorithms for selectively isolating the features of interest from the time series data.

論 文 審 査 の 結 果 の 要 旨

地球観測衛星によるリモートセンシングの我が国における研究開発、実利用化等の活動は、地球の諸現象に関する知見の獲得、地球環境変動観測、衛星地球観測の実利用化、およびナショナルセキュリティへの貢献などが考えられており、研究者がそれぞれの得意とする分野で鋭意推進することで、国民や社会の要請に応えていくことが期待されている。本論文の著者は、これまでの研究でリモートセンシング分野のうち、変形解析と特徴抽出を取り扱ってきた。地球観測衛星で得られるマルチスペクトルデータは、いくつかのバンド間で重なった情報が多いため、目的とする特徴を表す情報（テーマ的情報）を如何に上手く選択収集するかが根本の課題である。課題解決に向けて、「地方都市における土地被覆分類と熱特性」をテーマに、高精度の解析地図の作成に取り組んでいる。

地方都市として鳥取市及びその周辺を解析対象地域に選んでいる。この地域は地形及び社会的要素が平易かつ単純であり、モデル地区としては好適地である。衛星データは、主に LANDSAT/TM を使用し、データの解析処理を行う前に、全画像について厳密な幾何学的補正を行っている。すなわち、約 50 箇以上の選点について、一次元多項式と三次元たたみ込み内挿法を用いて幾何学補正を行ない、全画像を同じピクセルサイズ（30m）と同じ図法に変換するとともに、空間的誤差（地図上の誤差）をピクセルサイズの 0.5－0.6 倍（約 18m）の精度に改良し得たことは大きな成果である。

本題の、地方都市における土地被覆分類と熱特性について、まず、衛星データから時系列解析によってテーマ的情報を得る方法として、統計的手法のうちデータの変換による主成分分析（PCA）の適用性を検討している。PCA を用いて衛星データを変換すると、主成分として得られる情報は、互いに独立であって重なった情報はなく、第 2、第 3、第４、等、上位主成分のテーマ的情報（熱変化や土地被覆分類の変化）との合致度も良く、テーマとする情報を自動的に選択収集する有力な手段となりうることを見出した。例えば、熱赤外線 TM バンド６データを用いて行った鳥取市及び周辺地域の熱環境変化の PCA 解析の第 2 主成分地図は、従来の変形解析による熱変化地図とよく一致すること、さらにこれは、土地被覆分類の変化の解析を目的とする全 TM バンドを用いた PCA 解析の結果、第 8 主成分が示

す同地域の土地利用変化（従来の変形解析によって、これが都市域の拡大であり、農地の縮小であることが分かる）の解析地図ともよく一致することなど重要な結果を得ている。
このように、提案された主成分分析による衛星データの時系列解析手法は、変化の穏やかな地方都市の土地被覆分類や熱環境の年代的変化の解析に直ぐにも役立つであろうし、より根本的には本手法を用いてテーマ的情報を自動的に選択収集する可能性を示したことにより、今後の衛星データの自動解析技術の発展に大いに寄与するものと認め、その成果は博士（工学）の学位論文に値すると判定する。